Fiber Optics--A new method for monitoring stress changes

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ABSTRACT: Fiber optic based strain sensors have been developed that measure earth pressure loads. This paper describes the utilization of a borehole and cable sensor to monitor loads and vehicle type passing over a roadway. These sensors are shown to possess both high sensitivity and large dynamic range. These attributes make these sensors extremely useful for monitoring a variety of stress/strain situations.

1. INTRODUCTION

The motivation to pursue the application of fiber optics based technology to the development of new geophysical sensors at Los Alamos began in late 1983. The many benefits and advantages of the newly emerging optical fiber technology and the availability at reasonable cost of fiber optic components indicated that new and improved geophysical sensors should be developed. One type of geophysical sensor that would greatly benefit through the use of fiber optics was a borehole earth strain sensor for earthquake prediction research applications. A borehole sensor was developed and installed near Los Alamos in early 1986 to pursue these ideas, and has remained operational since then. In late 1986 DOE/Office of Arms Control began funding further sensor development for test ban verification applications under its' Technology Development program area. Since then, several improved versions of these snesors have been built and installed at various locations.

Fiber optics was developed and has had its greatest use in the area of telecommunications where its special properties are exploited to transmit large quantities of information at speeds previously unobtainable by more conventional methods. These special properties of fiber optics also can be used in the development of fiber optics based sensors for many applications. Fiber optics based sensors possess many advantages compared to conventional types of sensors. Some of their attributes are:

- High sensitivity,
- Large dynamic range,
- Wide frequency bandwidth,
- New sensor configurations or geometries,
- Near in-situ operation, and
- Reliable long lived operation.

There are two basic types of fiber optic sensors depending upon how one uses the optical fiber to measure the quantity of interest. In the first type, called *Amplitude Based Sensors*, the quantity being measured produces changes in the intensity of the light within the optical fiber. These sensors often only employ fiber optics to get the light into and out of the optical device that is making the desired measurement. Such problems as limited dynamic range, calibration, reproducibility, and drift usually limit the successful application of this type of sensor. This type of sensor has been successful in temperature, high pressure, high voltage, and chemical process measurements. Generally, the performance of this type of sensor is no better than existing conventional sensors, but sensor simplification and improved reliability may result because of the use of fiber optics. The second type of fiber optic sensors are those called *Phase Based Sensors* in which the quantity being measured produces changes in the phase of the light traveling within the fiber. This type of sensor, although more complex than the intensity type, can provide substantial improvements in sensor performance compared to conventional sensors. These sensors offer the important advantages of high sensitivity, very large dynamic range, and self calibration of the fiber optics. Thus they can offer substantial improvements in the sensor signal to noise ratio and adapt well to digital signal processing techniques. Their greater complexity of the hardware is usually offset by the improved sensor performance they provide. Successful sensors of this type measure rotation (fiber optic gyro), strain, underwater acoustics (hydrophone), and pressure.

One example of the Phase Based Sensor is the fiber optic interferometer shown in Fig. 1. In this interferometer, of the Mach-Zehnder type, the input light is split in coupler A into two beams which travel in fiber path 1 and fiber path 2 to coupler B where the two beams are recombined. If the two beams are in phase at this point the interferometer output is bright while if they are out of phase the output is dark. If path 1 is held constant while path 2 experiences a path length change (i.e., elongation or shortening) due to the parameter being measured, the output of the interferometer will change from light to dark in proportion to the change in length of path 2. These “fringe” changes are recorded as the sensor output signal and are proportional to the parameter being measured.

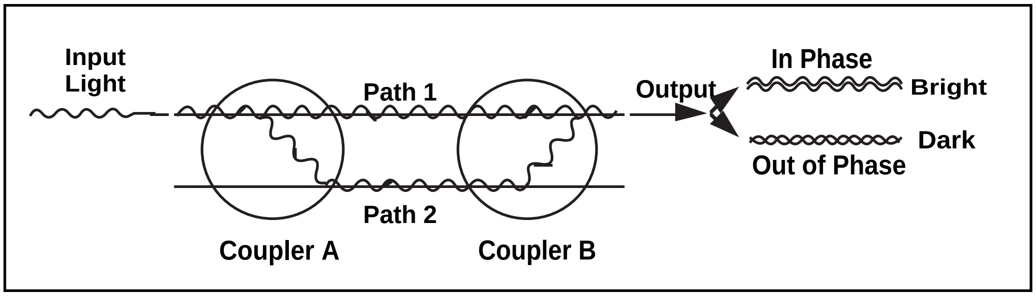

Fig. 1. Fiber optic interferometer.

2. MEASUREMENT PRINCIPLES

Fiber optic sensors have been developed to measure several geophysical phenomena. We have undertaken the measurement of borehole strain because of the many potential applications for this technology. Borehole strain (or earth strain) measurements also can provide data on the weight and characteristics of objects passing over the buried sensor. The basic principles of this type of measurement are shown in Fig. 2. A vehicle or other object passing over the sensor deforms the material and the sensor thereby producing a change in length of the optical fiber in the sensor. This length change is measured by the fiber optic interferometer and provides information about the object passing over the sensor.

The work we have previously done at Los Alamos demonstrates that these *in-situ* fiber optic earth strain sensors can provide a sensor capable of measuring both the “load” and “seismic” strain signals of any object that passes over or nearby the buried sensor. The “load” strain is the DC or very low frequency signal produced by the weight or weight distribution of the object as it passes over the sensor. The “seismic” strain is the 0.1 Hz to 250 Hz frequency signal produced by the active components of the object as it passes over or nearby the sensor. The “seismic” strain also has unique characteristics for each type of object that passes over the sensor since these signals are produced by the vehicles’ power plant or means of traction such as tank tracks. Examples of data presented later will show both the “load” and “seismic” strain signal characteristics discussed above. We have observed in sensor testing that once an in-situ sensor of this type is calibrated to various loads passing over it the measurement can be very accurate and reproducible.

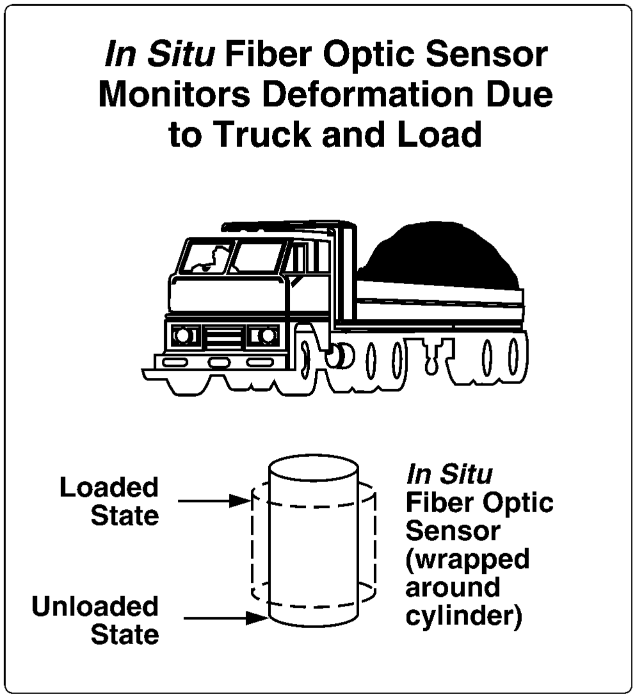

Fig. 2. Measuremement principles.

3. FIBER OPTIC SENSOR DESIGN

Two types of fiber optic sensors have been designed and used: *borehole* and *cable*. The basic sensor package design of the borehole type of sensor is shown in Fig. 3. The sensor element consists of a hollow PVC plastic mandrel about 10 cm in diameter that has single mode optical fiber wound around its outside diameter in a spiral that covers about one meter of the mandrel's length. The single mode optical fiber on the sensor element is configured as part of a fiber optic ring resonator interferometer that measures changes in the fiber's length due to changes in the mandrel's circumference. The sensor element is grouted in a borehole into contact with the earth medium. This produces a sensor that measures horizontal areal earth strain (the sum of the two principle horizontal strains). The sensor element is not responsive to horizontal shear strain but responds to vertical strains through the Poisson effect of the material in which the sensor is emplaced.

Another component of the borehole sensor package is the reference element that consists of 50 meters of single mode optical fiber wound around a separate mandrel located inside the sensor package. This mandrel is isolated from the earth strain signal and experiences a very stable thermal environment since the sensor is buried in a borehole. The single mode optical fiber on the reference element is also configured as a fiber optic ring resonator interferometer and serves as a very stable standard of length that is used to stabilize the 1319 nm wavelength laser that illuminates the interferometer.

Because the borehole sensor package is essentially empty, weight must be added so that it will not float in the grout mixture used to emplace the sensor in the borehole. An epoxy and sand mixture in the proportion of about 30%/70% (epoxy/sand) is used as a relatively rapid (two week) curing permanent grout that shows none of the long term curing effects as seen in cement based grouts that can adversely affect the performance of this high sensitivity sensor.

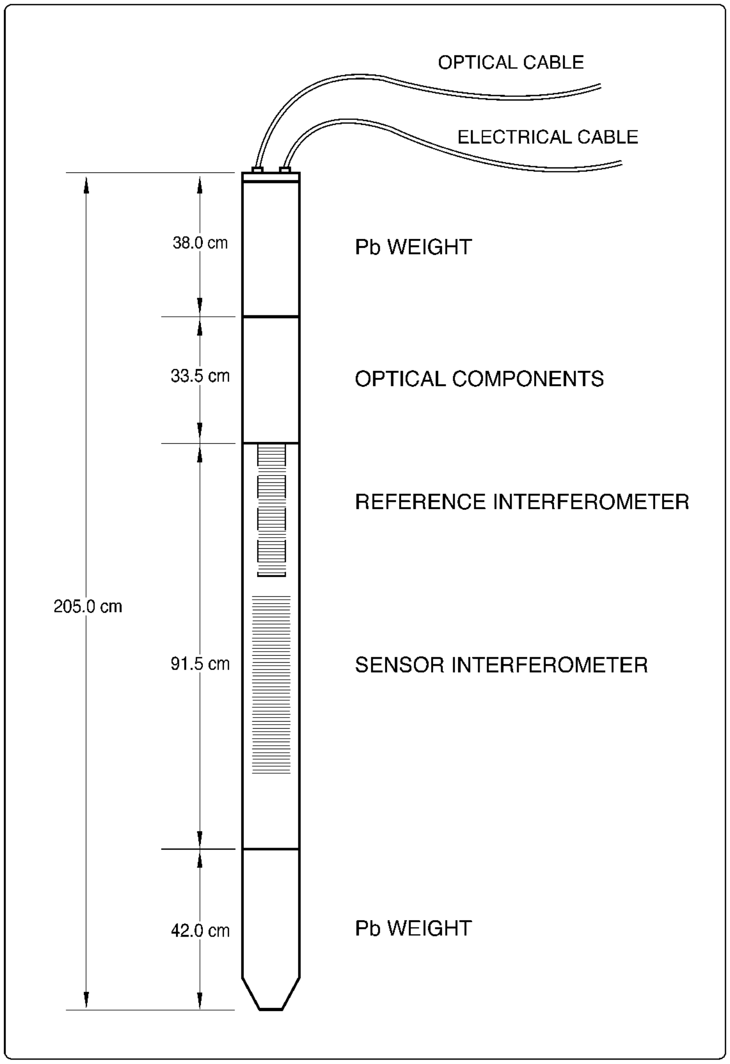

Fig. 3. Borehole sensor design.

A second type of fiber optic sensor, a cable sensor, was developed to measure strains near the surface of the earth. The sensing element in this sensor consists of a fiber optic cable made up of many single mode optical fibers in a bundle that is buried in a shallow trench. The single mode fibers in the sensor cable are configured in a fiber optic ring resonator interferometer to provide measurement of changes in the length of the cable due to earth strain acting upon the cable. The sensor cable length may be any length up to several kilometers.

4. READOUT SYSTEM DESIGN

The main characteristic of all (both bulk optic and fiber optic) interferometers is that the optical output changes from light to dark (i.e,. fringes) as the phase changes within the interferometer because of the optical path length changes caused by the signal being measured by the sensor. However, this optical output does not provide information on the sense or direction of the change in the optical path length (elongation or shortening) taking place within the interferometer. Thus some other means must be employed to determine the direction or sense of change within the interferometer. One such means is to generate a quadrature or phase dependent signal thereby eliminating the sense or direction ambiguity.

A 3X3 fiber coupler is used from which two optical output signals with a quadrature like relationship are produced (Fig. 4). With the second optical signal being out of phase from the first it is possible to determine fringe sense or direction and use the signal for fringe counting by a small PC computer system. The dynamic range and the frequency bandwidth of the sensor system then depends on the speed of the photodetectors, A to D converters, and the PC. Also the system is flexible to changing conditions and can be reprogrammed for different applications with relative ease.

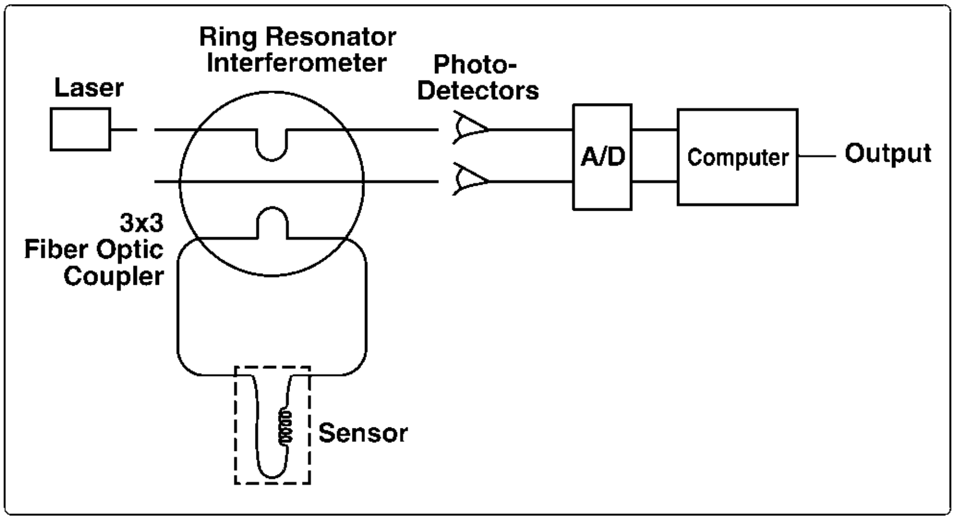

Fig. 4. A high finesse sensor using a ring resonator interferometer constructed from a 3x3 coupler to count fringes.

The use of a particular type of interferometer within the sensor can have a significant effect upon the type of optical signal produced and the ability to accurately readout that signal. Within the current sensor configuration, a ring resonator interferometer is used. This interferometer produces a high finesse output. The advantage of a high finesse output are that the fringes are well defined and easy to count. In addition, a high finesse output is more resistant to noise and requires less computational power to process the signal. The disadvantage of a high finesse interferometer counting system is that no information is present between fringes thus lowering the resolution of the sensor to whole fringes. However, this can be overcome by using a longer length of optical fiber in the sensor element.

The use of optical quadrature detection and fringe counting ideally lends itself to the measurement of a wide range of load magnitudes (i.e., provides a large dynamic range for the sensor). The vehicles to be monitored and measured are heavy enough to produce many fringe counts for accurate weighing and the seismic signature will contain a wide frequency bandwidth signal because of the propulsion system thereby providing a method for vehicle identification.This system produces a digital output that is ready for recording and on-line or future processing.

5. INSTALLATION OF FIBER OPTIC SENSORS AT WHITE SANDS MISSILE RANGE

In July of 1991 an extensive series of loading tests were conducted at the White Sands Missile Range in south central New Mexico using these sensors. Two boreholes and one

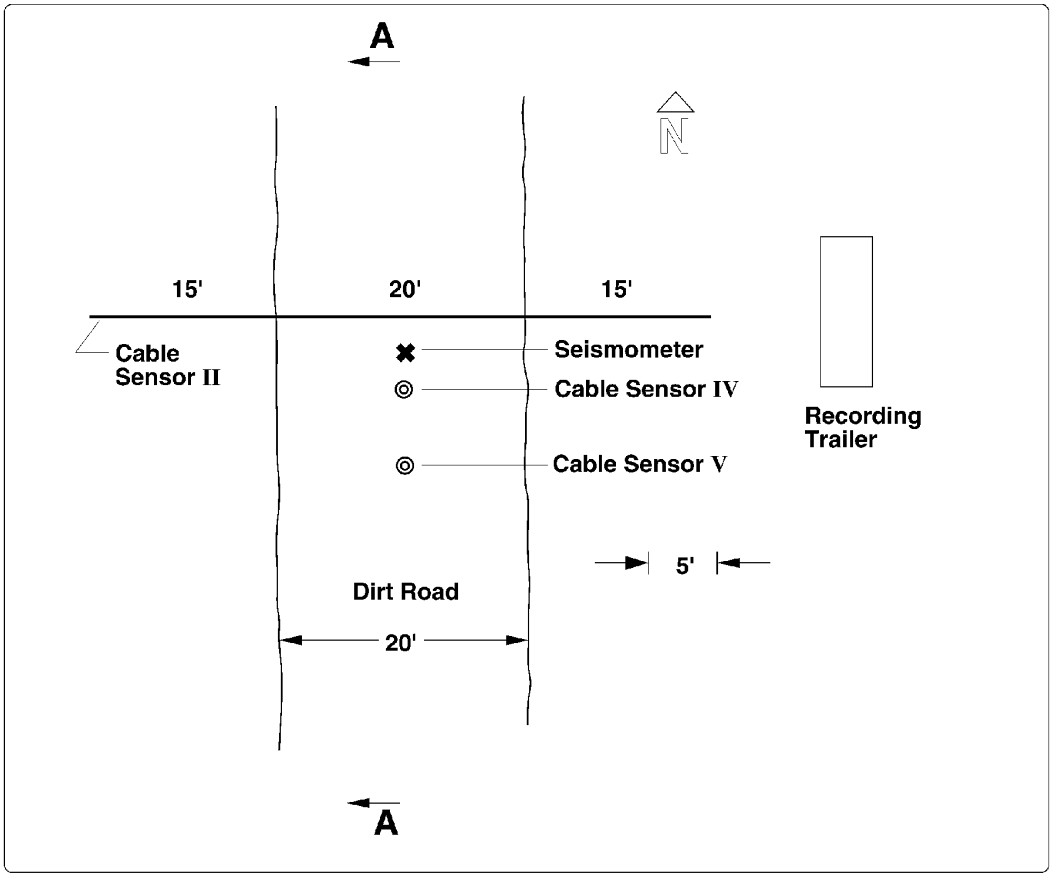

Fig. 5. Plan view of field installation.

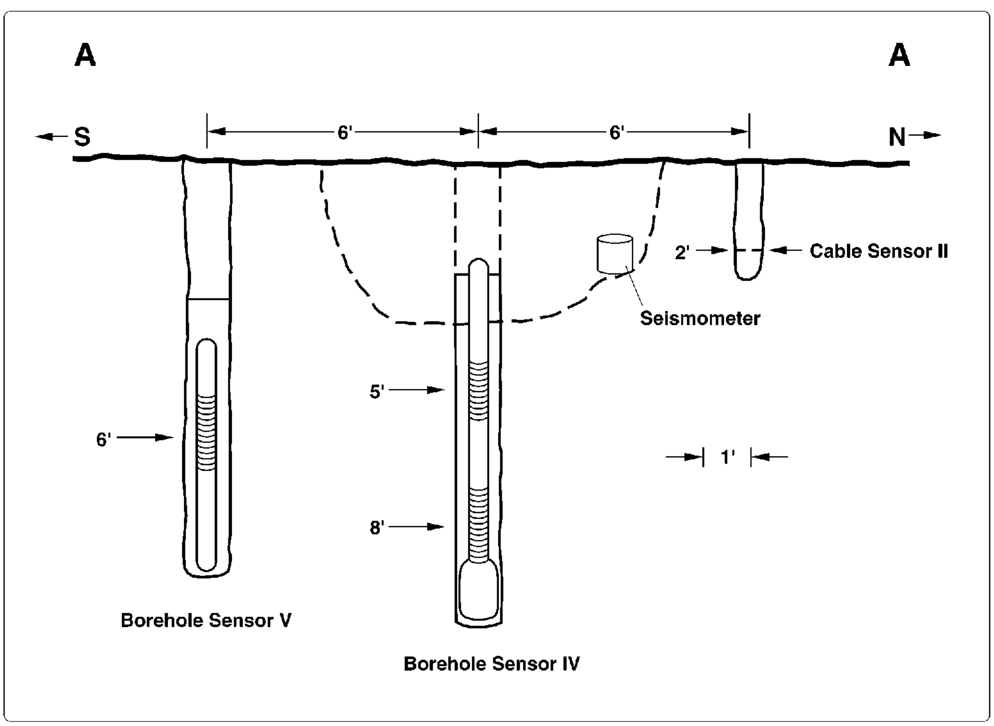

Fig. 6. Cross section of field installation.

cable sensor was installed in a 20 foot wide dirt road at the Dirt Site located in the southeast corner of the Range (Fig. 5). The borehole IV sensor had two strain sensor elements with 500 meters of optical fiber centered at 5 foot and 8 foot borehole depths respectively. The borehole V sensor had a single strain sensor element with 125 meters of optical fiber centered at 6 foot borehole depth (Fig. 6). Both of these sensors were configured to measure areal strain and were installed in the middle of the dirt road (Fig. 5). The cable sensor had a 50 foot cable sensor element containing 732 meters of optical fiber that ran across (perpendicular to) the dirt road (Fig. 6) and was buried at a depth of 2 feet (Fig. 6). A conventional seismic sensor (seismometer) was also buried at a 2 foot depth in the middle of the road (Fig. 5).

The recording trailer that contained the sensor illumination and readout system was connected to the fiber optic sensors in the road by means of fiber optic cables. The fiber optic sensors are non-electrical devices that only operate on the light sent from the trailer and return the light to the readout system in the trailer. Thus they were impervious to the many near-by lightning strikes produced by the many afternoon thunderstorms common at that time of year.

6. RESULTS OF FIELD LOADING TESTS

Loading tests were performed on a variety of moving objects ranging in weight from individuals (150-200 lbs; Fig. 7), a pickup truck (3500 lbs; Figs. 8 and 9), to an M-1 tank (130,000 lbs: Fig. 10). This demonstrates the tremendous range of weight that the sensors were capable of detecting. In all these cases, vehicles moved over the sensors at 5 mph with the peak dc offset being when the vehicle was centered over the sensor. The sensor is capable of measuring both the dc (weight) and ac (motion) portions of the vehicle signature. The large high frequency oscillations shown in Fig. 10 are not systematic noise but are in fact caused by vehicle treads striking the ground as the vehicle is moving. To demonstrate that idea, Fig. 11 shows an M-60 tank (100,000 lbs) parked on a sensor.

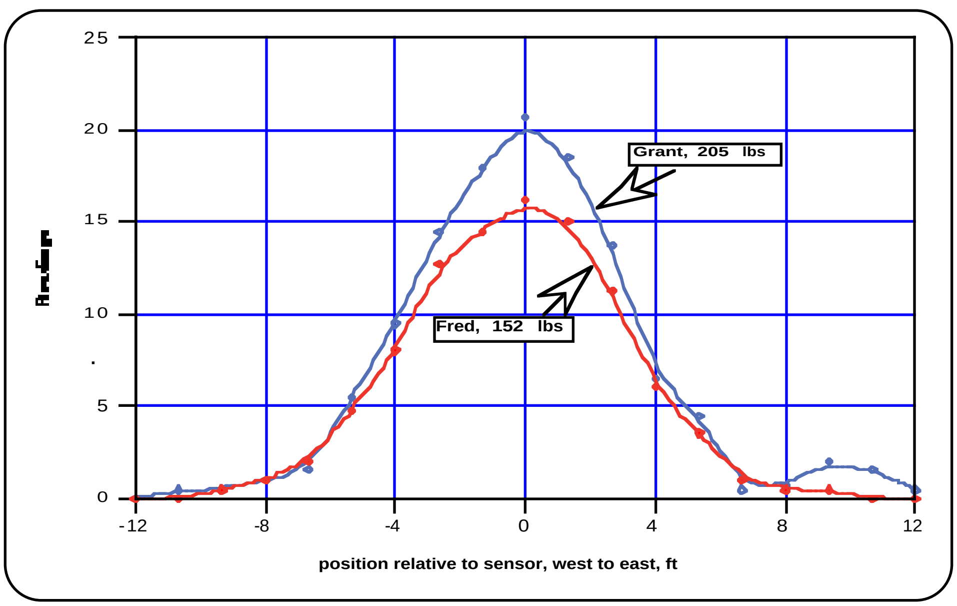

Fig. 7. Two people walking over borehole sensor.

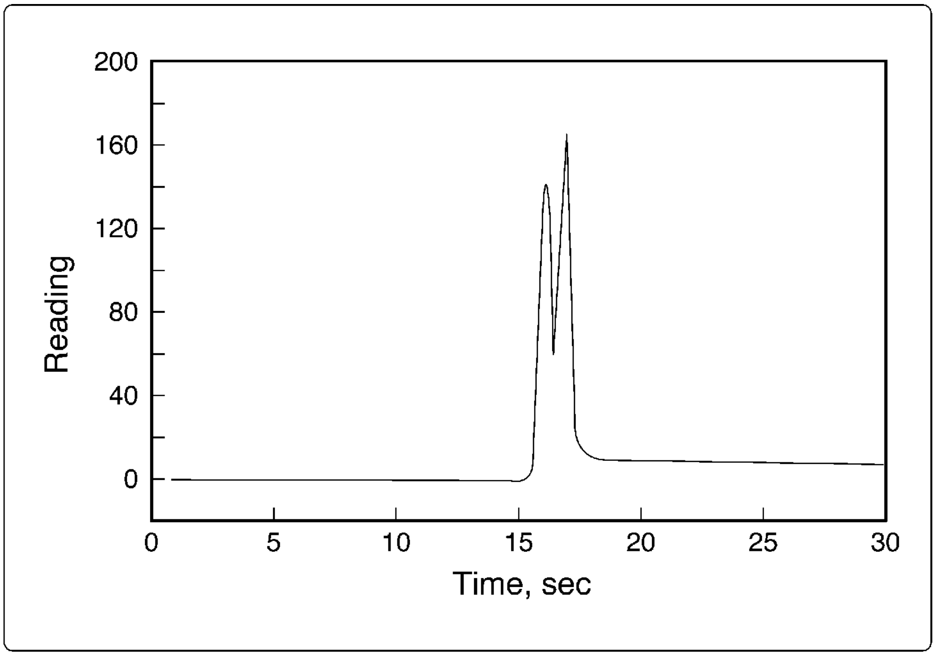

Fig. 8. Detection of pickup truck driving over borehole sensor, 5 mph.

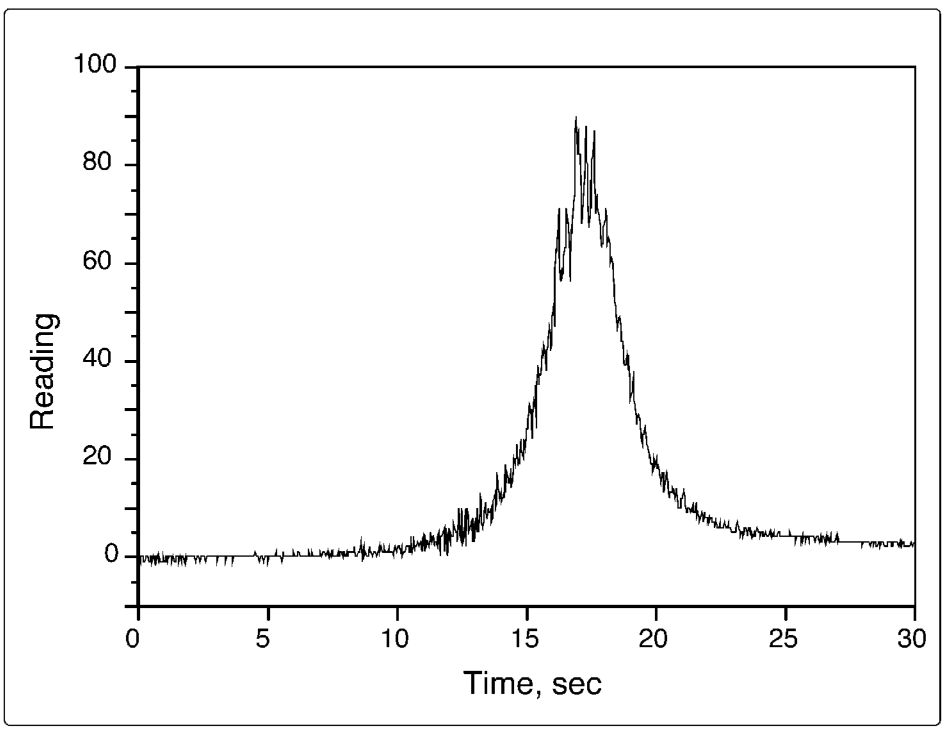

Fig. 9. Pickup truck driving over cable sensor, 5 mph.

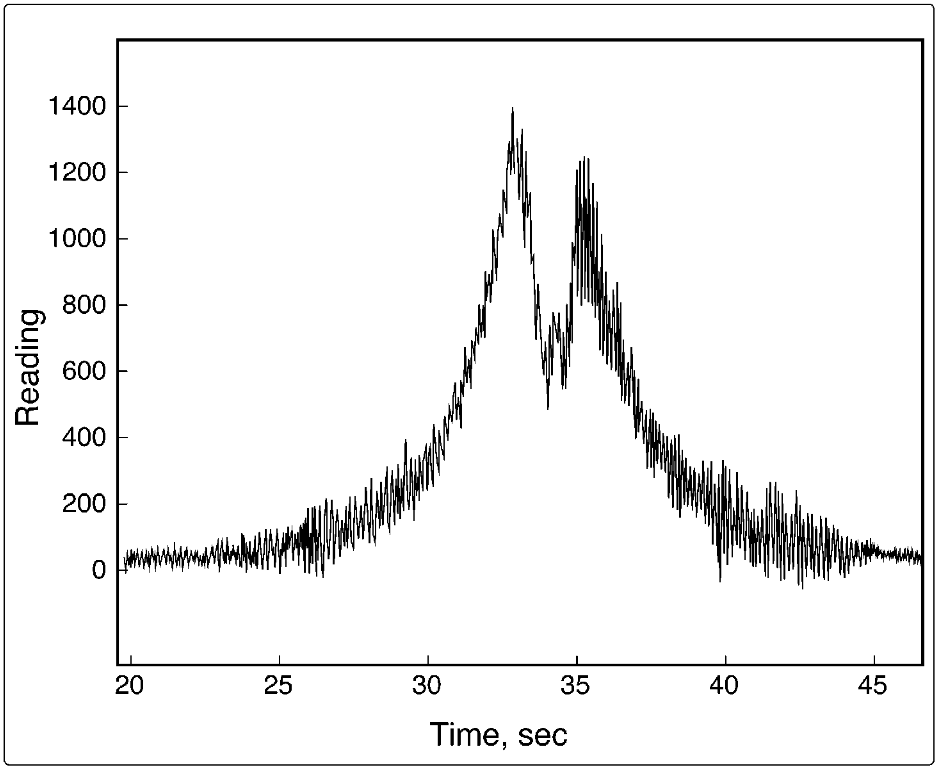

Fig. 10. M1 tank driving over borehole sensor, 5 mph.

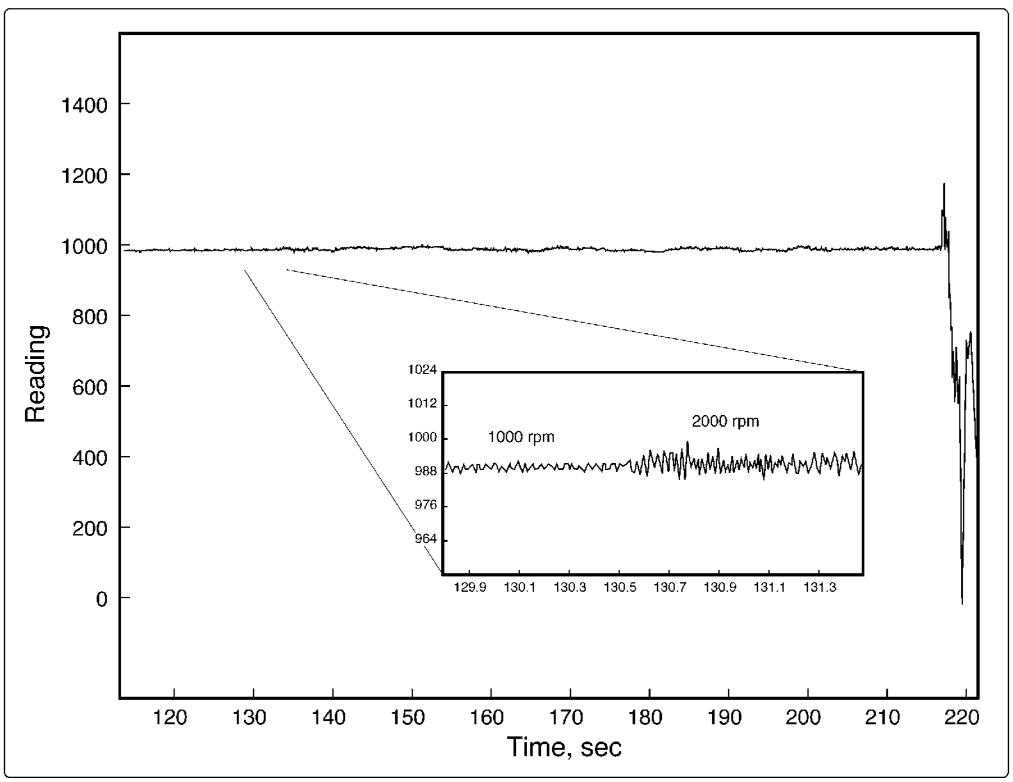

Fig. 11. M60 tank driving over borehole sensor.

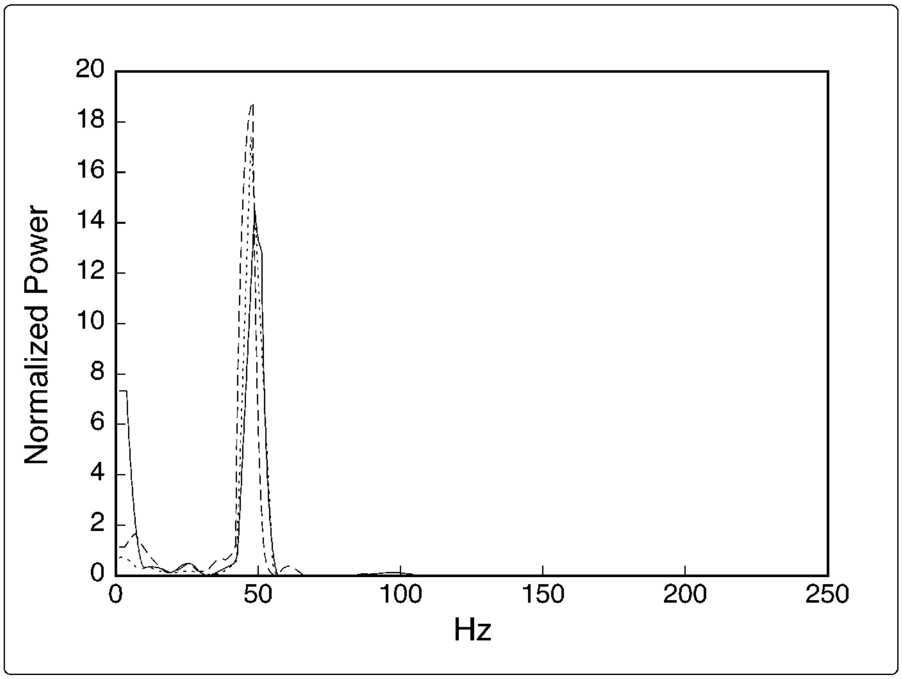

Fig. 12. Frequency spectra of 3 runs of an M1 tank moving at 5 mph.

Figure 12 shows three M-1 tank runs over the sensor at 5 MPH in frequency space. The principal frequency characteristic is clearly visible in all three runs. This figure demonstrates the repeatability of sensor reading as well as highlighting the ability of the sensor to discriminate different vehicles based on the frequency content of their signatures.

7. CONCLUSIONS AND FURTHER WORK

The loading tests at White Sands Missile Range successfully demonstrated several of the key features of phase-based fiber optic sensors. Those features include sensitivity, dynamic range and repeatability. Additional analysis is being done to explore the ability of the sensor to discriminate between types of vehicles and objects and perhaps even between individual vehicles and objects.

This type of sensor also should be very useful in monitoring stress changes underground. With this in mind, Los Alamos is working with the Pittsburgh office of the U.S. Bureau of Mines to install a prototype in certain underground coal mines. Additionally, the sensor could be used to monitor and record dynamic (e.g., rockbursts) signals as well.

8. ACKNOWLEDGEMENTS

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